# Final Report for DE-FG02-96ER14685, Laser-Produced Coherent X-Ray Sources

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## 1 Program Scope:

We study the generation of x-rays from the interaction of relativistic electrons with ultra-intense laser pulse either directly or via laser generated ion channels. The laser pulse acts as the accelerator and wiggler leading to an all-optical synchrotron-like x-ray source. The mm sized accelerator and micron-sized wiggler leads to a compact source of high brightness, ultrafast x-rays with applications in relativistic nonlinear optics, ultrafast chemistry, biology, inner-shell electronic processes and phase transitions.

## 2 ACCOMPLISHMENTS

### 2.1 Optical deflection and temporal characterization of an ultra-fast laser-produced electron beam

At ultra-high laser intensities, the magnetic field of the light pulse leads to significant longitudinal electron motion. This has led to proposals for "vacuum acceleration," whereby free electrons would be injected into an ultra-high intensity laser pulse to produce GeV electron beams. An experiment by Malka *et al.* , showed that an electron could be accelerated to almost 1 MeV by all-optical techniques. However the model used to analyze these results employed fields that did not obey Maxwell's equations. A more complete model based on previous theoretical and experimental work shows the crucial role of longitudinal fields for tightly focused, high intensity laser pulses. In addition to the basic physical questions which need to be answered, a direct measurement of the temporal profile of the electron bunch would serve to elucidate the underlying mechanism as well as a precise estimate of the x-ray pulse from an all-optical synchrotron-like source. Recently, electro-optic techniques have been developed to measure the duration of picosecond electron bunches, whereas optical techniques could achieve a resolution $< 30$ fs.

In order to investigate these questions, we have studied the interaction of a laser produced electron beam with an ultra-intense laser pulse in a "colliding" geometry, where the two intersect at an angle of 135 deg. At relativistic intensities, the light pulse imparts longitudinal momentum to the electron beam, leading to the beam being deflected. In the experiment, the primary laser pulse (P) produces a wakefield accelerated electron beam with a divergence of 1-degree. The second laser pulse when spatiotemporally overlapped with the electron beam, deflects it by as much as 3-degrees. The latter is accomplished by solving the equation of motion $md(\gamma \mathbf{v})/dt = -e[\mathbf{E} + \mathbf{v} \times \mathbf{B}]$ for an electron subjected to a linearly polarized, focused Gaussian laser pulse with finite temporal extent. An approximate expression for the laser field may be found in terms of a series expansion based on the expansion parameter $\epsilon = 1/k_0 w_0$ where $\mathbf{k}_0$ is the wave vector of the laser pulse and $w_0$ is the focused spot size. To the best of our knowledge, we have shown for the first time that the longitudinal fields that are present at the focus of a high intensity laser pulse modify the trajectory of the electron beam at relativistic intensities. Another outcome of this study is that, as the delay between the electron bunch and the optical pulse was varied, we were able to determine that the temporal duration of the electron beam is of the order of 1 ps.

## 2.2 Conditioning of laser-produced electron beams

The all-optical technique discussed in the previous subsection is capable of generating quasi-monoenergetic, ultrafast, tunable, MeV-scale energy electron beams with low transverse and longitudinal emittance. When electrons collide obliquely with an intense laser beam, the electromagnetic pulse imparts a small amount of its forward momentum to the particles thereby deflecting them. Salamin and Faisal have shown that a one-to-one correspondence between this scattering angle and the incident particle energy for a given laser intensity. This selectivity can, thus, be exploited to remove electrons of a given energy from a finite temperature beam. Following an oblique laser-electron beam collision, the desired electron energy is collected through a slit placed at the preselected angle. In fact, in this way, several energies can be chosen in a single shot by employing several such slits.

Self-modulated laser driven wakefield accelerated electron beams are natural source beams for this scheme. They possess large energy spreads ensuring that the desired energy range will be well populated regardless of shot-to-shot variations. These beams can also be inherently synchronized with the deflecting beam by splitting an initial laser pulse and employing one part to drive the electron beam and the other to implement the deflection. In this way too, the conditioned electron beam naturally inherits the small spatial ($\sim\mu$m) and temporal ($10's$ fs) scales of the laser. This matches the sizes of the electron beam and deflecting laser maximizing the geometric efficiency and automatically generating particle beams ideal for simultaneous high spatial and temporal resolution imaging.

Specifically, using an incident electron beam temperature of 18 MeV as reported by Malka *et al.* and laser intensities of $9\times10^{18}$ and $4\times10^{19}$ W cm$^{-2}$, we have demonstrated generation of electron beams with energies of 1200$\pm$450, 2350 $\pm$450, 3000$\pm$650, and 2850$\pm$325 keV, and durations $\leq$ 30 fs containing $10^8-10^9$ electrons are produced in both single particle and particle-in-cell (PIC) simulations. A Maxwellian electron beam traveling along $\hat{\mathbf{y}}$ collides with a 1 $\mu$m laser pulse, linearly polarized along $\hat{\mathbf{x}}$ , propagating along $\hat{\mathbf{z}}$, and having a duration of 30 fs focused down to a spot $10\mu$ in diameter.

Preliminary single particle and particle-in-cell calculations of electron beam conditioning using the laser parameters expected at the UNL facility have demonstrated the separation of $\sim$ 500 pC of charge at energies of $1\pm0.4$, $2\pm0.3$, and $3\pm0.3$ MeV from a 5 nC Maxwellian beam with an initial temperature of 18 MeV. The preformed electron beam collides with the deflecting laser pulse at an angle of 90 degrees. Initially, the beam is Maxwellian. After deflection, the electrons deflected between 5 and 10 degrees are Gaussian in energy with $< E >= 1.04$ MeV. This model included 1304325 particles each tracked independently by solving the relativistic equation of motion for a Hermite-Gaussian (0, 0) mode laser including the first non-paraxial spatial and temporal corrective terms using a fifth order Runge Kutta method. Work is ongoing to fully characterize the duration and transverse emittance of these conditioned beams as well as the relationship among the incident electron and laser beam parameters including particle energy, laser intensity, electron and laser pulse duration, an the laser spot size.

## 2.3 All optical x-ray source using colliding laser and electron beams

The interaction of a laser generated electron beam with an ultra-intense laser pulse in the previously described geometry was also used to generate XUV radiation from a synchrotron-like mechanism. We have experimentally observed Thomson scattering from laser-accelerated electrons using a 10 TW, 400 fs Nd:Glass laser split into two pulses. A narrow-divergence MeV electron beam of nC charge is generated by focusing 80% of the beam energy to an intensity of $4\times10^{18}$ in an under-dense He plasma which produces a baseline Thomson scattered signal from the interaction of the electron beam with the laser pulse that produced it. The remaining 20% of the laser energy is focused to $1\times10^{18}$ and directed into the interaction region at 135 deg. With the introduction of the second laser pulse, an enhancement in the radiation signal of up to 100% in the harmonic peaks is observed in the imaging VUV spectrographs.

With short pulses the generation of soft x-rays from the self-interaction of laser-generated electrons with the laser pulse that produced it has also been demonstrated. X-ray radiation from the nonlinear Thomson scattering of a 30 fs/1.5 J laser beam on plasma electrons has been observed. A collimated x-ray radiation with a broad continuous spectrum peaked at 0.15 keV with a significant tail up to 2 keV has been observed. These characteristics are found to depend strongly on the laser strength parameter $a_0$. This radiative process is dominant for $a_0$ greater than unity at which point the relativistic scattering of the laser light originates from MeV energy electrons inside the plasma.

## 2.4 Production of keV x-ray beam from synchrotron radiation

It has been demonstrated that a beam of x-ray radiation can be generated by simply focusing a single high-intensity laser pulse into a gas jet. A millimeter-scale laser-produced plasma creates, accelerates, and wiggles an ultrashort and relativistic electron bunch. As they propagate in the ion channel produced in the wake of the laser pulse, the accelerated electrons undergo betatron oscillations, generating a femtosecond pulse of synchrotron radiation, which has keV energy and lies within a narrow (50 mrad) cone angle.

The experiment was performed with titanium-doped sapphire (Ti:sapphire) laser operating at 10 Hz with a wavelength of 820 nm in chirped-pulse amplification mode. The laser delivered energies up to 1 J on target in 30 fs, with a linear horizontal polarization. The laser beam was focused with an $f = 18$ off-axis parabolic mirror onto the edge of a supersonic helium gas jet (diameter 3 mm) with intensities on the order of $3\times\ 10^{18}$ W cm$^{-2}$, for which the corresponding normalized vector potential $a_0$ is 1.2. By using a magnetic spectrometer, the electron beam temperature was determined to be 20 MeV.

The x-ray radiation produced in the plasma was measured using a cooled x-ray CCD camera placed directly on the laser axis without any focusing x-ray optic. For all the measurement, a 25 $\mu$m beryllium filter is kept in front of the CCD camera to block any radiation below 0.8 keV. The spectrum of the radiation was determined by using an additional set of aluminum, nickel, and copper filters. The spectral and angular features of the x-ray emission as well as its dependency on the electronic density of the plasma have been characterized experimentally. The experimental results are found to be in good agreement with the numerical simulations and the analytical estimations describing the radiation emitted by the trapped electrons undergoing betatron oscillations in the ion channel.

Initially, x rays were detected from 1 to 6 keV. The back-illuminated CCD, which is not sensitive to energies above 10 keV, did not allow a full spectral characterization of the radiation. The total number of photons integrated over the bandwidths of the filters is more than $10^8$ photons, per shot and integrated over all angles, which is in close agreement with the result expected from the simulation. Second, the radiation is found to be collimated in a narrow cone centered on the laser axis. For plasma parameters at which the x-ray intensity is maximum, the spatial distribution is larger than the size of the CCD area (using our experimental setup) and is obtained by rotating the x-ray CCD around the gas jet. The x-ray beam divergence, averaged over more than ten shots, is found to be $\Delta\theta$=50$\pm$20 mrad at FWHM. More collimated x-ray beams have been observed at slightly lower electron density where the x-ray signal is weaker. The beam divergence can reach 20 mrad (FWHM) in that case. A third striking feature of the observed x-ray emission is its intensity as a function of the electron density of the plasma. We found that the radiative process is more efficient at the plasma density $n_e = 1.1 \times 10^{19}$ cm$^{-3}$ at which the x-ray intensity is sharply peaked.

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